CHAPTER 5

THE RELIABILITY-CENTERED MAINTENANCE PROCESS

5-1. Overview

The overall RCM process was introduced in chapter 2 and is depicted in the process flow chart, figure 2-1. This chapter will describe in more detail how the process is implemented.

5-2. C4ISR candidates for RCM analysis

Is important to note from the onset that an RCM analysis is not beneficial for all products. The criteria listed in table 5-1 will help the analyst determine if an RCM analysis is potentially of value. There are three major systems comprising C4ISR facilities that are candidates for RCM analysis, mechanical systems, electrical systems, and control systems. All three combine to support the facilities mission and provide the necessary environmental conditions to maintain operation of critical equipment and personnel. All of the components shown in paragraph 5-2 are candidates for RCM optimization and require a maintenance program geared toward the mission requirement of the facility.

Table 5-1. Criteria for applying RCM to products

Criteria	Comment
Product has or is projected to have a large number of PM tasks.	Existing product already in service or new system for which the PM tasks were identified using an approach other than RCM.
Product maintenance costs are or are projected to be very high.	Existing product already in service. PM tasks either identified using an approach other than RCM or RCM requires updating. New system for which maintenance tasks were identified using an approach other than RCM.
Product requires or is projected to require frequent corrective maintenance.	Existing product already in service. PM program may be inadequate; either identified using an approach other than RCM or RCM requires updating. New system for which maintenance tasks were identified using an approach other than RCM.
Hazardous conditions could result from failure.	New product, or existing product for which the PM tasks were identified using an approach other than RCM.

a. *Mechanical systems.* The types of mechanical systems typical for a C4ISR facility include those shown in table 5-2.

Table 5-2. Types of mechanical systems typical for a C4ISR facility

• Chillers	• Boilers
• Cooling towers	• HVAC distribution equipment including Fan Coil Units
• Valves	• Control systems (Supervisory Control and Data Acquisition [SCADA])
• Piping	

(1) *Other systems.* Mechanical systems also include generators, fuel oil delivery systems and storage and pumping components. These are critical to the mission of the facility but are frequently neglected.

(2) *Temperatures.* Mechanical systems not only maintain a comfortable environment for the occupants but are also designed to maintain optimal equipment operating temperatures.

b. *Electrical systems.* Electrical systems begin at the transformer feeding the building or the 13.8 v feeder and continue through the entire distribution system generally to the panels containing the 208 or 220/120-volt distribution. Some facility mission requirements require solutions all the way to the operating equipment at the wall outlet. Typical components comprising the electrical system include those shown in table 5-3.

Table 5-3. Typical components comprising the C4ISR facility electrical system

• Transformers, liquid filled and air cooled	• Motor Control Centers
• Connections	• Motors
• Cables	• Cable Connections
• Switch Gear	• UPS systems including Gel and Wet Cell Lead Acid Batteries
• Circuit Breakers	

c. *Control systems.* Control systems are the third major component making a C4ISR facility as reliable as possible. Control systems are the brains behind the operational characteristics during normal and abnormal conditions. Control systems are commonly identified as Supervisory Control and Data Acquisition (SCADA) systems and are designed to monitor conditions and react in a manner to maintain a set point. Typical SCADA systems are comprised of a series of sensors sending signals to a central command center where the signals are interpreted. Signals are sent from the command center to actuators to throttle input conditions and provide the necessary environmental condition required for the mission operations. Typical components for a SCADA system are shown in table 5-4.

Table 5-4. Typical components for a SCADA system

- Computer access panel
- Digital drivers
- Power Supplies
- PLC
- Interface devices such as control panels or flying circuit breakers.

5-3. RCM data sources

Conducting an RCM analysis requires an extensive amount of information. Since much of this information is not available early in the design phase, RCM analysis for a new product cannot be completed until just prior to production. Table 5-5 lists some general sources of data for the RCM analysis. The data elements from the Failure Modes and Effects Analysis (FMEA) that are applicable to RCM analysis are highlighted in paragraph 55b. Note that when RCM is being applied to a product already in use (or when a maintenance program is updated during Life Exploration – see paragraph 55e), historical maintenance and failure data will be inputs for the analysis.

Table 5-5. General data sources for the RCM analysis

Data Source	Comment
Lubrication requirements	Determined by designer. For off-the-shelf items being integrated into the product, lubrication requirements and instructions may be available.
Repair manuals	For off-the-shelf items being integrated into the product.
Engineering drawings	For new and off-the-shelf items being integrated into the product.
Repair parts lists	
Quality deficiency reports	For off-the-shelf items being integrated into the product.
Other technical documentation	For new and off-the-shelf items being integrated into the product.
Recorded observations	From test of new items and field use of off-the-shelf items being integrated into the product.
Hardware block diagrams	For new and off-the-shelf items being integrated into the product.
Bill of Materials	For new and off-the-shelf items being integrated into the product.
Functional block diagrams	For new and off-the-shelf items being integrated into the product.
Existing maintenance plans	For off-the-shelf items being integrated into the product. Also may be useful if the new product is a small evolutionary improvement of a previous product.
Maintenance technical orders/manuals	For off-the-shelf items being integrated into the product.
Discussions with maintenance personnel and field operators	For off-the-shelf items being integrated into the product. Also may be useful if the new product is a small evolutionary improvement of a previous product.
Results of FMEA, FTA, and other reliability analyses	For new and off-the-shelf items being integrated into the product. Results may not be readily available for the latter.
Results of Maintenance task analysis	For new and off-the-shelf items being integrated into the product. Results may not be readily available for the latter.

a. *C4ISR data sources.* RCM related data may be obtained from several different types of sources. Some potential sources of maintainability data include those shown in table 5-6.

Table 5-6. Potential sources of C4ISR maintainability data

- Historical data from similar products used in similar conditions (PREP Database, IEEE Gold Book)
- Product design or manufacturing data
- Test data recoded during demonstration testing
- Field data

(1) *Expressing data.* The data maybe expressed in a variety of terms. These include observed values or modified values (true, predicted, estimated, extrapolated, etc.) of the various maintainability measures. Some precautions are therefore necessary regarding the understanding and use of such data as shown in table 5-7.

Table 5-7. Understanding and using different sources of data

- Historical – Used primarily during the concept definition phase to generate specifications requirements. In latter phases historical data may be compared with actual data obtained for the product. They can also serve as additional sources of information for maintainability verification.
- Product Design and Manufacturing – Data obtained through the use of design analysis or prediction, or from data generated during the design phase or the manufacturing phase. Design data may be used as the basis for product qualification and acceptance, review and assessment of historical data relevancy and the validity or previous assessments. Before this type of data is used in your analysis you must understand the data collection and analysis methodology, why the specific method was chosen, and any possible limitations.
- Product Demonstration and Field – These data are essential for sustaining engineering activities during the in-service phase of the system life cycle. They include maintainability related data obtained from formal or informal demonstration test on mock-ups, prototypes or production equipment in either a true or simulated environment or data generated during actual item use.

(2) *Other data categories.* Other categories of data that would be beneficial to collect include information on the maintenance support conditions. Operational maintainability may not be determined solely by inherent maintainability, but by logistical factors. Therefore information to be collected should include shortages in spares (due to inadequate initial provisioning, long pipeline times, etc.), test resources, and human resources. Such data are important to determine why a system's maintainability as measured in the field, may not be meeting the values expected based on the design data.

(3) *SCADA systems.* SCADA systems are excellent data collection mechanisms, providing the system is initially design to capture critical information. It can also be utilized to monitor trends of component operational conditions to provide information on proactive logistics supplies.

5-4. PM tasks under RCM

a. *Lubrication and servicing task.* Many mechanical items in which movement occurs require lubrication. Examples include internal combustion engines that require oil and periodic replacement of that oil (and associated filters). Lubrication and servicing tasks are sometimes overlooked due their relative simplicity and because they are "obvious." Prior to the latest version of the airline's RCM approach, lubrication and servicing tasks were often omitted from the decision logic tree, with the understanding that such tasks cannot be ignored. In the current MSG-3, these tasks are explicitly included in the decision logic, as they are in this document.

b. *Inspection or functional check task.* Inspections normally refer to examinations of items to ensure that no damage, failure, or other anomalies exist. Inspections can be made of: an entire area (e.g., the body or "under the hood"), a subsystem (e.g., the engine, controls, or feed mechanism), and a specific item, installation, or assembly (e.g., the battery, shaft, or flywheel).

(1) *Visual inspections or checks.* These are checks conducted to determine that an item is performing its intended function. The check may be performed by physically operating the item and observing parameters on

displays or gauges, or by visually looking to see if the function is being performed properly. In neither case are quantitative tolerances required. A functional check consists of operating an item and comparing its operation with some pre-established standard. Functional checks often involve checking the output of an item (e.g., pressure, torque, voltage, or power) and checking to determine if the output is acceptable (i.e., within a pre-established range, greater than a pre-established minimum value, or less than a pre-established maximum value). These checks are conducted as failure-finding tasks.

(2) *Use of NDI.* Inspections may consist of purely visual examinations or be made using special techniques or equipment. Many inspections require the special capability of non-destructive inspection (NDI) techniques. Table 5-8 lists some of the NDI methods available to maintenance personnel.

c. *Restoration task.* Many items, primarily mechanical, wear out as they are used. At some point, it may be necessary, and possible, to restore the item to "like new" condition. Examples include internal combustion engines, electric motors, and pumps.

d. *Discard task.* Some items upon failure or after their useful life has been reached (i.e., they are worn out), cannot be repaired or restored. These items must be discarded and replaced with a new item identical in function. Examples include seals, fan belts, gaskets, screws (stripped threads), and oil filters.

5-5. The RCM process

a. *Identify the system configuration.* Since the RCM analysis usually begins before the final design has been completed, the system configuration is changing. Even when the design is complete, model changes can be made. The configuration, of course, determines how functions are performed, the relationship of items within a product, and so forth. Consequently it is important that the precise configuration of the product or system for which the RCM analysis is being conducted be documented as part of the analysis. It is also important that the analysis be updated to account for any changes in the configuration (some of which may be required as a direct result of the RCM analysis itself).

b. *Perform an FMEA and other analyses.* To perform the RCM analysis, many pieces of information are needed. These include the information shown in table 5-9. Obviously, such information will probably not be known or be very shaky early in design. For that reason, the RCM analysis should not be started until sufficient and reasonably stable information is available. Of course, the objective is to develop and complete the initial maintenance program prior to the product being transferred to the customer.

(1) *Other inputs.* When FTAs are needed to understand the effects of, for example, multiple failures, the information derived from these analyses can also be valuable inputs to the RCM analysis.

Table 5-8. NDI techniques

NDE Method \ Main Application		C	W	F	CR	E	L	MA	MC	S	D	MT	DT	PR	OTHER	Legend: C = Cracks; W = Wear; F = Fractures; CR = Corrosion; E = Erosion; L = Leaks; MA = Material Analysis; MC = Material Conditions; S = Stress; D = Deformation; MT = Material Thickness; DT = Deposit Thickness; PR = Physical Restrictions **Remarks**
1	Acoustic cross correlation						X									Locating buried pipes
2	Acoustic emission	X		X			X		X		X				X	Internal structural noise
3	Coating thickness												X		X	Magnetic methods and eddy currents. Ferrite content of ferritic-austenitic steels
4	Dye penetrant	X		X			X									Including the chalk, water, alcohol methods
5	Eddy current testing	X	X	X	X	X	X				X	X			X	Heat exchanger tubes, wire rope, surface checks, sorting
6	Emission spectroscopy (Metascope)							X								Low and high alloy steels. Including X-ray fluorescence
7	Endoscopy	X	X	X	X	X	X						X	X		Inspection of internal surface
8	ER-probe				X											Average corrosion rates
9	Ferrography		X													Lubricated mechanical systems
10	Hardness testing								X							Brinell, Vickers, Rockwell B, C&N, Rockwell superficial, Knoop, Shore, Scleroscope, Equotip, UCI
11	Hydrogen cell				X											Average corrosion rates
12	Isotope techniques		X				X		X			X	X	X	X	Tracer tech., ball test, radiometry, collim. Photon
13	Laser distance measurements (optocator)		X									X			X	Topography, symmetry
14	Leak testing resistance						X								X	Liquid penetrant, ultrasonics, pressure change, foam, tracers, sulphur diffusion, ozalide paper, halogen
15	LPR-probe, polarization				X											Instantaneous corrosion rate
16	Magnetic plugs		X													Lubricated mechanical systems
17	Magnetic particle examination	X													X	Weld defects, laminations – only ferromagnetic materials
18	Mechanical calibration		X		X	X						X	X		X	Physical dimensions
19	NDE method combination	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Check of entire component condition. Predictive programs
20	NDE meth. under. dev.	(X)							(X)	(X)	(X)				(X)	
	20.1 SPAT									X						Stress pattern analysis by thermal emission
	20.2 Pulsed video thermography (PVT)								X						X	Composite materials. Glued metals, delamination, and coatings.

Table 5-8. NDI techniques (Cont'd)

Main Application / NDE Method		C	W	F	CR	E	L	MA	MC	S	D	MT	DT	PR	OTHER	Legend: C = Cracks; W = Wear; F = Fractures; CR = Corrosion; E = Erosion; L = Leaks; MA = Material Analysis; MC = Material Conditions; S = Stress; D = Deformation; MT = Material Thickness; DT = Deposit Thickness; PR = Physical Restrictions **Remarks**
	20.3 Moire contour										X				X	Topography
	20.4 Holographic interferometry (HI)									X					X	Lack of adhesion, material defects, thin samples
	20.5 Computerized tomography (CT)	X													X	Annual rings, knots, moisture, concrete column cross sections
	20.6 Positron annihilation								X						X	Voids in metals. Fatigue in titanium
21	Noise measurements														X	Noise level, bearing checks
22	Pattern recognition	X	X	X	X	X					X	X	X	X		
23	P-scan	X	X	X	X	X						X			X	Weld inspection, stress corrosion, corrosion topography, creep defects. Full documentation
24	Pinhole														X	Coatings, high/low voltage
25	Pressure testing	X		X			X				X					Including vacuum testing. See also leak
26	Radiography	X	X	X	X	X	X					X	X	X	X	Check of joints, geometry, laminations, reinforced concrete and corrosion/erosion
27	Replica technique	X	X	X					X		X				X	Surface microstructure, crack type, wear grooves, topography
28	Spectrometric oil analysis program		X													Lubricated mechanical systems
29	Strain gauge technique									X	X					Weight, pressure, oscillation
30	Stroboscopy	X	X	X											X	Visual condition monitoring, rotation direction and rate
31	Test coupons				X	X										Average corrosion rate
32	Thermography	X			X		X						X		X	Surface temp., bearing pressure, moisture, energy loss
33	Ultrasonic lea, detection						X								X	Electrical discharge, flow
34	Ultrasonics	X	X	X	X	X	X		X	X	X	X				Including sound attenuation
35	Vibration monitoring	X	X	X											X	Machinery include bearings, gears, turbines, centrifuges, etc.
36	Visual inspection	X	X	X	X	X	X	X			X		X	X		Spark pattern & chemical analysis
37	X-ray crawlers														X	Checking welds inside pipes
38	X-ray diffraction									X						Measurement residual stresses

Table 5-9. Information needed for RCM

The types of failures that can occur in the product
The failure characteristics of the items that make up the product being analyzed
The nature of the failures (hidden, evident, safety, operational, etc.)
The capabilities of the maintenance organization
The maintenance concept
A thorough understanding of operation

(2) *Other information.* Other important sources of information for the RCM analysis include Reliability Block Diagrams (RBDs), Functional Block Diagrams, system requirements documents, descriptions of system applications, technical manuals/drawings/layouts, and indenture level identification system.

(3) *Sources.* To provide the needed information, various sources must be exploited. One of the most obvious sources is the body of analyses conducted as part of the design process. These include the Failure Mode and Effects Analysis (FMEA) or Failure Modes, and Effects, and Criticality Analysis (FMECA), Fault Tree Analysis (FTA), maintainability analysis, and so forth.

(4) *FMEA.* The FMEA can be a primary source of much of the information needed for the RCM analysis. Figure 5-1 shows excerpts of the form prescribed in the Automotive Industry Group standard on FMEA/FMECA. Upon examining figure 5-1, it is obvious that the data in many of the columns can be directly used for the RCM analysis. The columns having data most applicable for the RCM analysis are shaded. In addition to those shown column can be added for functions, functional failure, failure modes, failure mechanism, failure detection method, compensating provisions, severity class, and three columns for failure effects: local effects, next higher level, and end effects.

Form from the Automotive Industry Group Standard on FMEA

Item/ Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	SEV	CLASS	Potential Cause(s)/ Mechanisms of Failure	OCC	Current Design Controls	DET	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Action Results				
												Action Taken	New Sev	New Occ	New Det	New RPN

Figure 5-1. Data elements from FMEA that are applicable to RCM analysis.

Legend: SEV – Severity of failure effect
OCC – Probability of occurrence
DET – Method of detection
RPN – Risk Priority Number

c. *Apply RCM decision logic.* The overall decision logic for applying the RCM methodology is depicted in figure 5-2. The decision logic represented in this figure is adapted from that used in the Reliability Analysis Center's Master Steering Group –3 (MSG-3). The most significant difference is in the portions of the tree labeled ②, ④, ⑦, and ⑧. MSG-1 through MSG-3 (see paragraph 1-6) used the term "safety" for these portions of the tree.

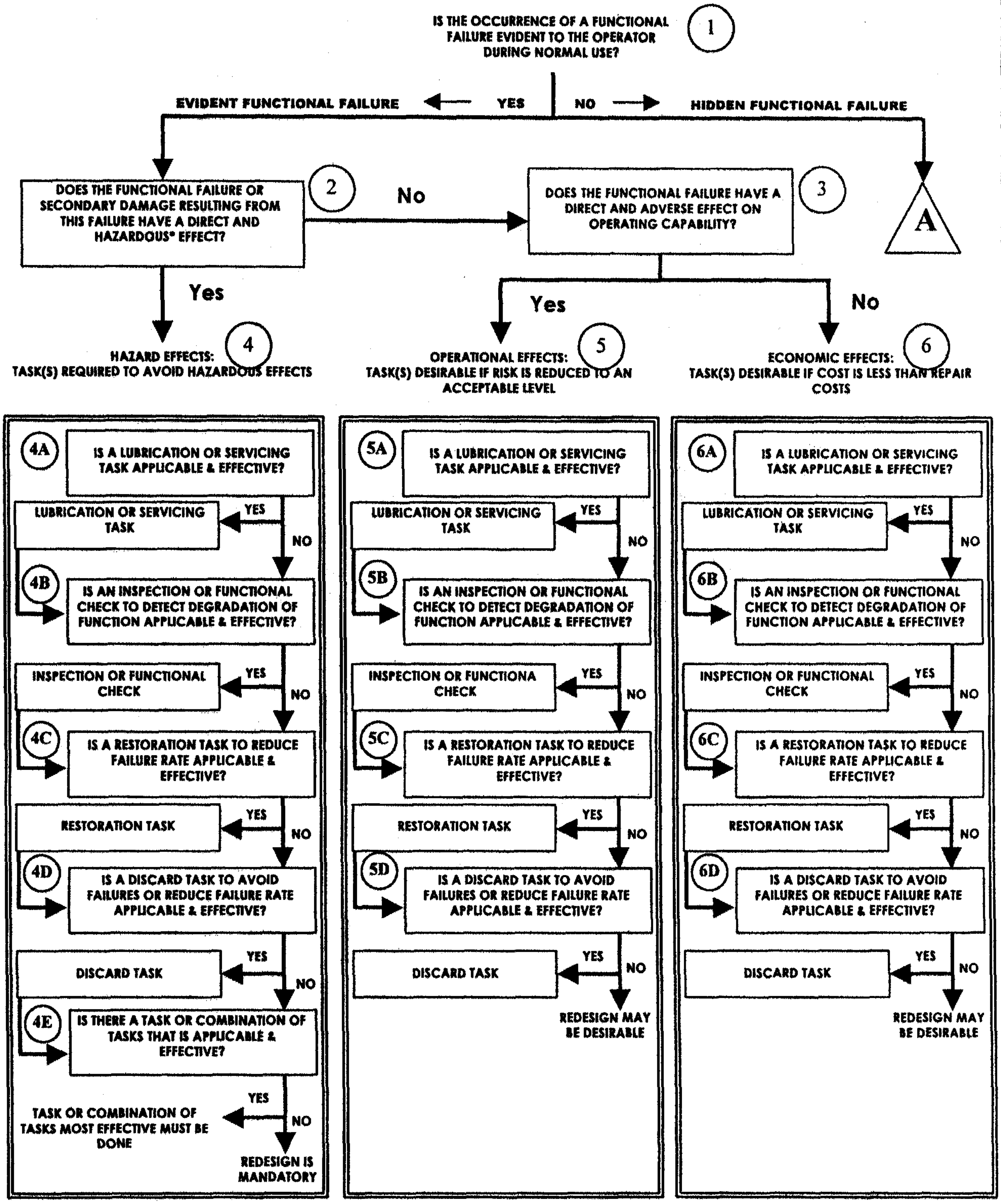
(1) *Safety.* Obviously, safety is of paramount importance to the airline industry, as it is in other industries, such as the nuclear power industry.

(2) *Other Critical Considerations.* Many industries have concerns that are as important, or nearly so, as safety considerations. The petroleum and chemical industries, for example, are subject to severe economic and even criminal penalties under Federal statutes for events in which the environment is polluted. For other industries, failures that result in the violation of other Federal, state, or local statutes, or in other unacceptable consequences may be treated as seriously as safety-related failures are in the airline industry. For that reason, in the portions of the tree labeled ②, ④, ⑦, and ⑧, the term "hazardous effects" is used rather than "safety effects". (The circled numbers in this and following discussions refer to a corresponding numbered portion of the referenced figures.)

d. *Use of Logic Tree.* As can be seen from figure 5-2, the decision logic tree consists of a series of Yes-No questions. The answers to these questions lead to a specific path through the tree. The questions are structured to meet the objectives of the RCM analysis: ensure the safe (non-hazardous) and economical operation and support of a product while maximizing the availability of that product. This objective is met by selecting preventive maintenance (PM) tasks when appropriate, redesign, some combination of PM and redesign, and by corrective maintenance (CM) when PM is either applicable or effective.

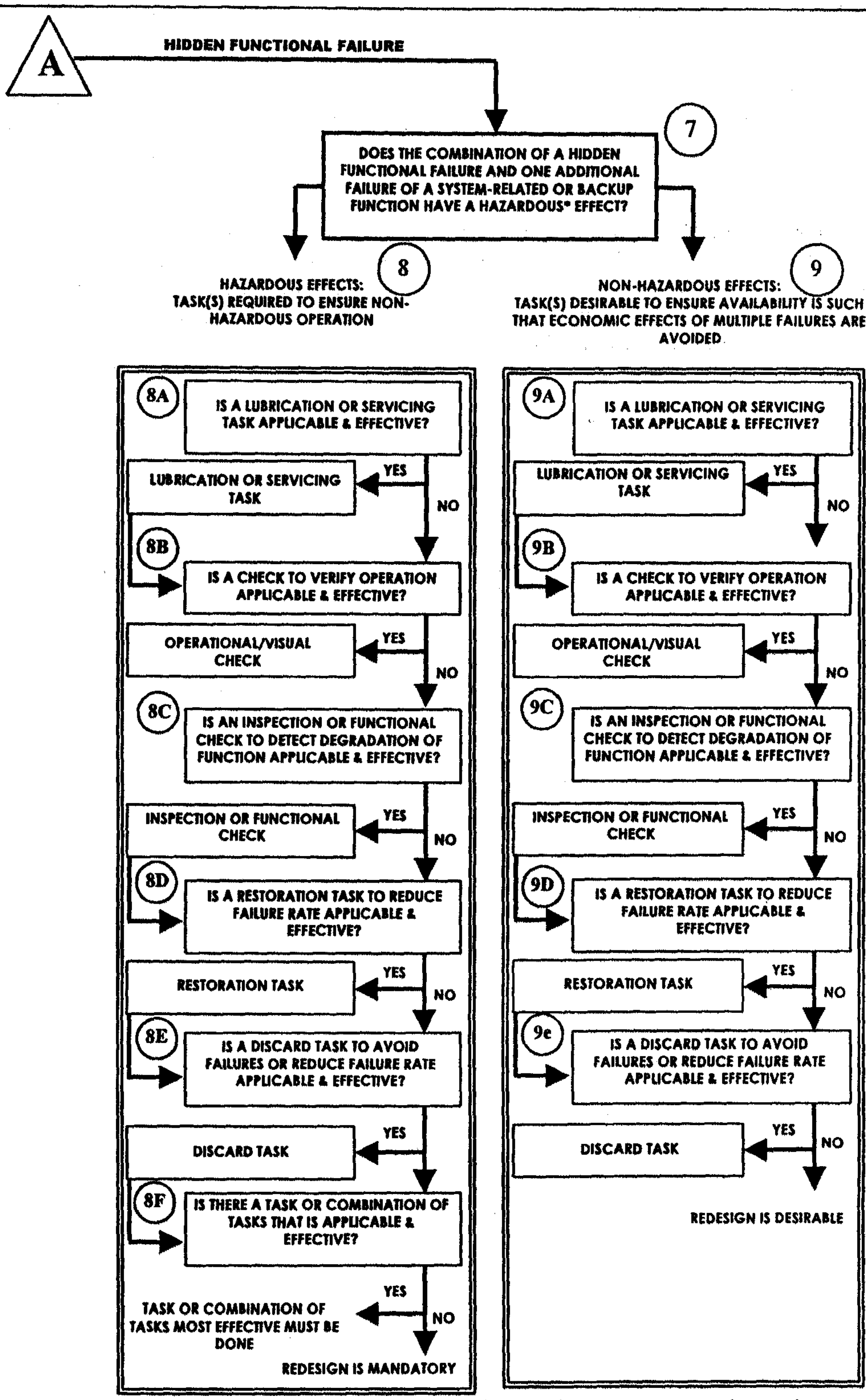
(1) The first question asked is "Is the occurrence of a functional failure evident to the operator (or user) during normal use?" A "No" answer means that the failure is hidden, and the analyst is directed to ⑦ in the tree. The portion of the tree below ⑦ is discussed under paragraphs 55h and 55i. A "Yes" answer means that the failure can be observed or is made known to the operator/user, in which case, the analyst is directed to ②.

(2) At ② , the question is "Does the (evident) functional failure or secondary damage resulting from the functional failure have a direct and hazardous effect?" A "Yes" answer directs the analyst to ④. The portion of the tree below ④ is discussed under paragraph 55e. A "No" answer directs the analyst to ③. The portion of the tree below ③ is discussed under paragraphs 55f and 55g.



*Hazardous effects include property damage, injury or death to operators or other people, violation of Federal environmental or health statutes, and other effects determined by the company or industry to be serious or catastrophic.

Figure 5-2. RCM decision logic tree (adapted from MSG-3).



*Hazardous effects include property damage, injury or death to operators or other people, violation of Federal environmental or health statutes, and other effects determined by the company or industry to be serious or catastrophic.

Figure 5-2. RCM decision logic tree (adapted from MSG-3) (Cont'd).

e. Evident Failure – Hazardous Effects. The portion of the decision logic tree that deals with situations where an evident functional failure has hazardous effects is shown in figure 5-3.

(1) This portion of the tree steps the analyst through a series of questions intended to identify any and all PM tasks that will reduce to an acceptable level the probability of occurrence of the functional failure that results in the effects, reduce the effects to purely operational or economic effects, or result in a combination of these two improvements.

(2) If none of the PM tasks listed is either applicable or effective, then redesign is mandatory. The reason for making redesign mandatory is obvious. The effects categorized as "hazardous" are unacceptable. Consequently, when PM cannot fulfill any of the objectives listed, we must redesign the product to eliminate the mode of failure that causes the hazardous effects, reduce to an acceptable level the probability of occurrence of the functional failure that results in the effects, or result in a combination of these two improvements.

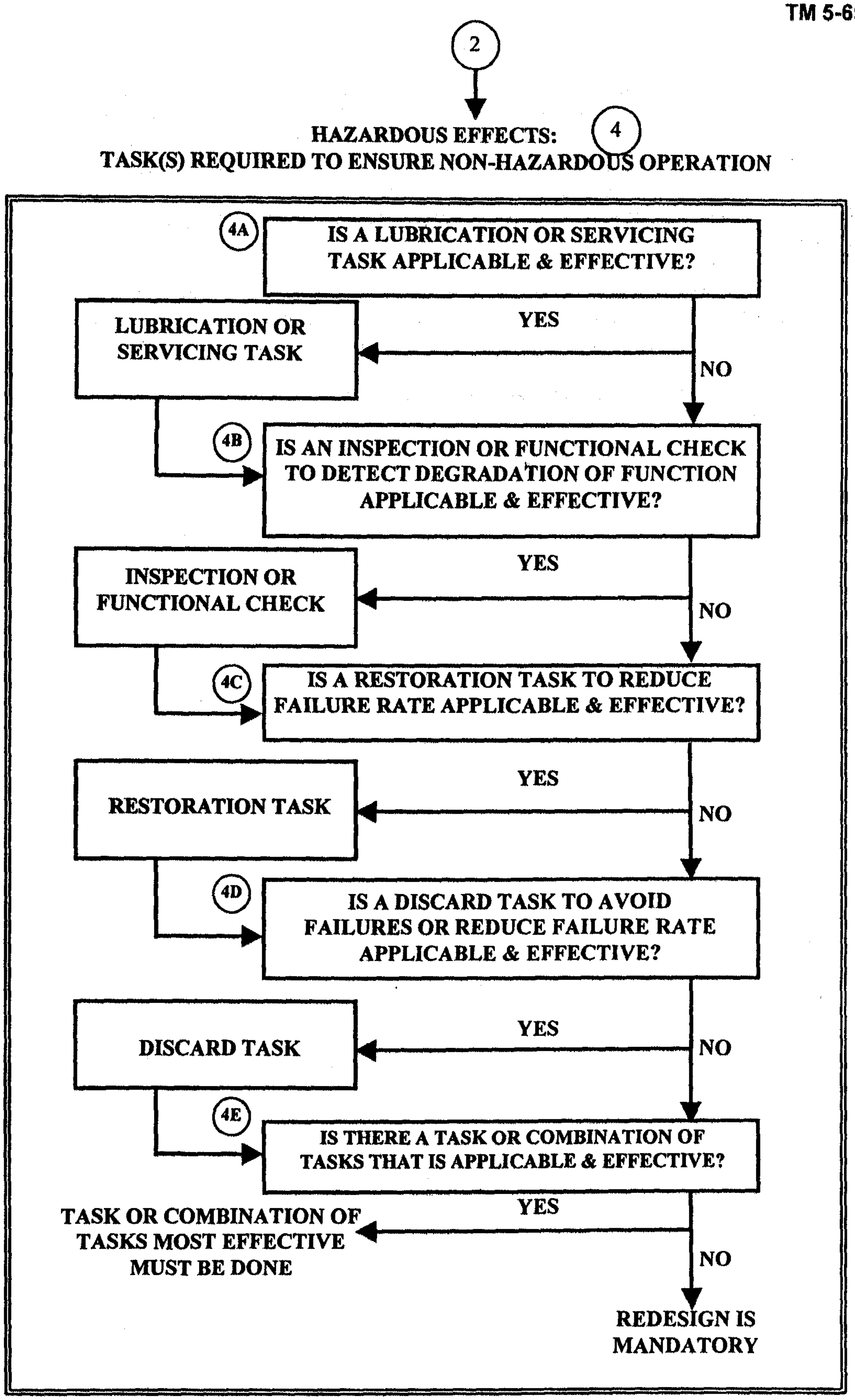


Figure 5-3. Evident failure – hazardous effects.

f. *Evident Failure – Operational Effects.* The portion of the decision logic tree that deals with situations where an evident functional failure has a direct and adverse effect on operating capability is shown in figure 5-4. This portion of the tree steps the analyst through a series of questions intended to identify any and all PM tasks that will reduce the risk of failure to an acceptable level. If none of the PM tasks listed is either applicable or effective, then redesign may be desirable. The cost of a functional failure that results in operational effects includes both the cost of the PM and the economic cost incurred as a result of the end system not completing a mission or being able to perform its function(s).

(1) If the costs exceed the cost to redesign the product, redesign is economically justified. The purpose of the redesign would be to eliminate the mode of failure that causes the operational effects, reduce to an acceptable level the probability of occurrence of the functional failure that results in the effects, or some combination of these.

(2) Even if redesign is economically justified, other considerations, such as schedule, may outweigh the advantages gained.

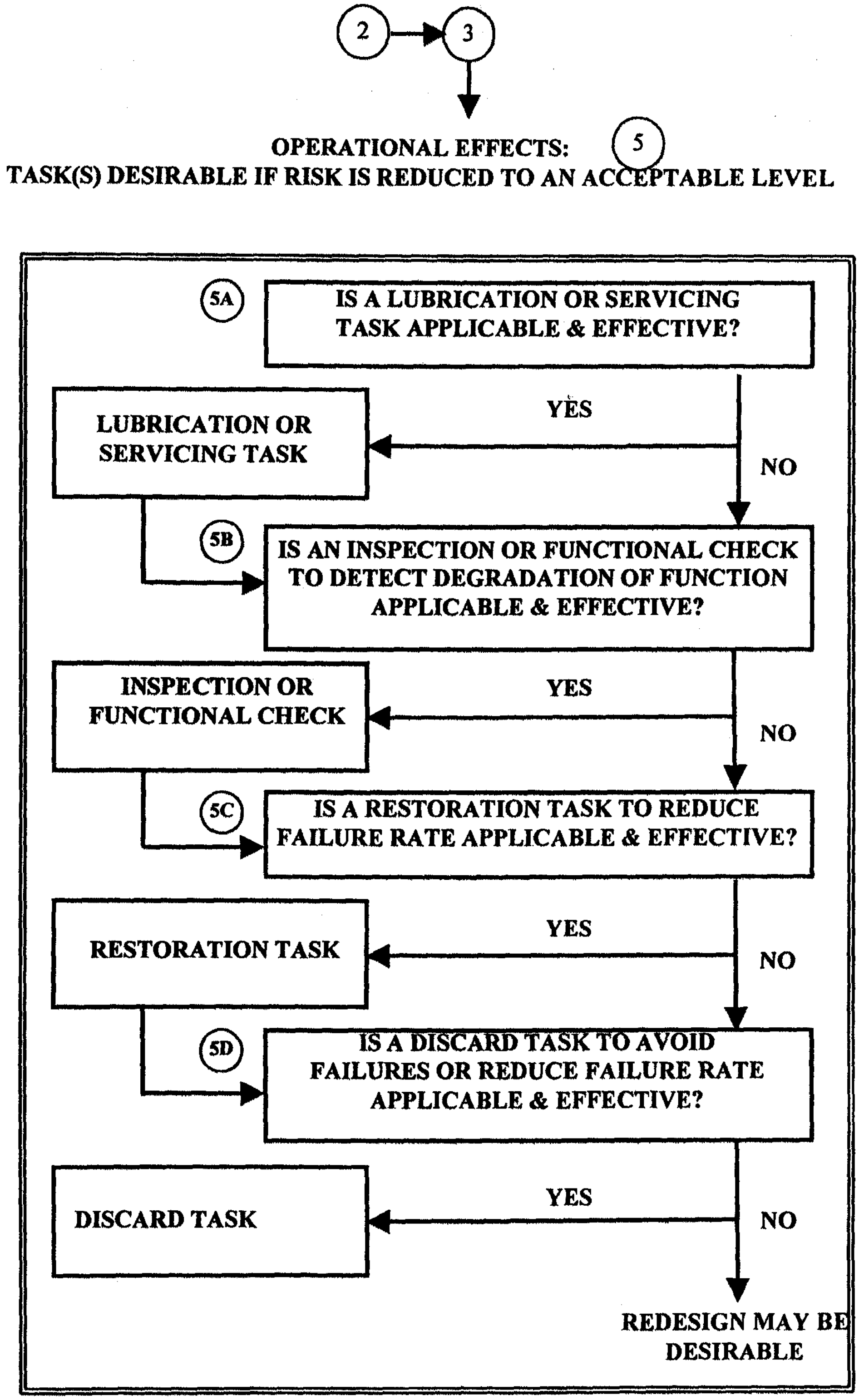


Figure 5-4. Evident failure – operational effects.

g. *Evident Failure – Economic Effects*. The portion of the decision logic tree that deals with situations where an evident functional failure has only an economic effect is shown in figure 5-5. This portion of the tree steps the analyst through a series of questions intended to identify any and all PM tasks that are desirable if their costs are less than the cost of repair. If none of the PM tasks listed is either applicable or effective, then redesign may be desirable. Again, the decision to redesign or not redesign is one of economics. If redesign is less than the economic effects of the failure, then it may be desirable. Otherwise, redesign is not justified.

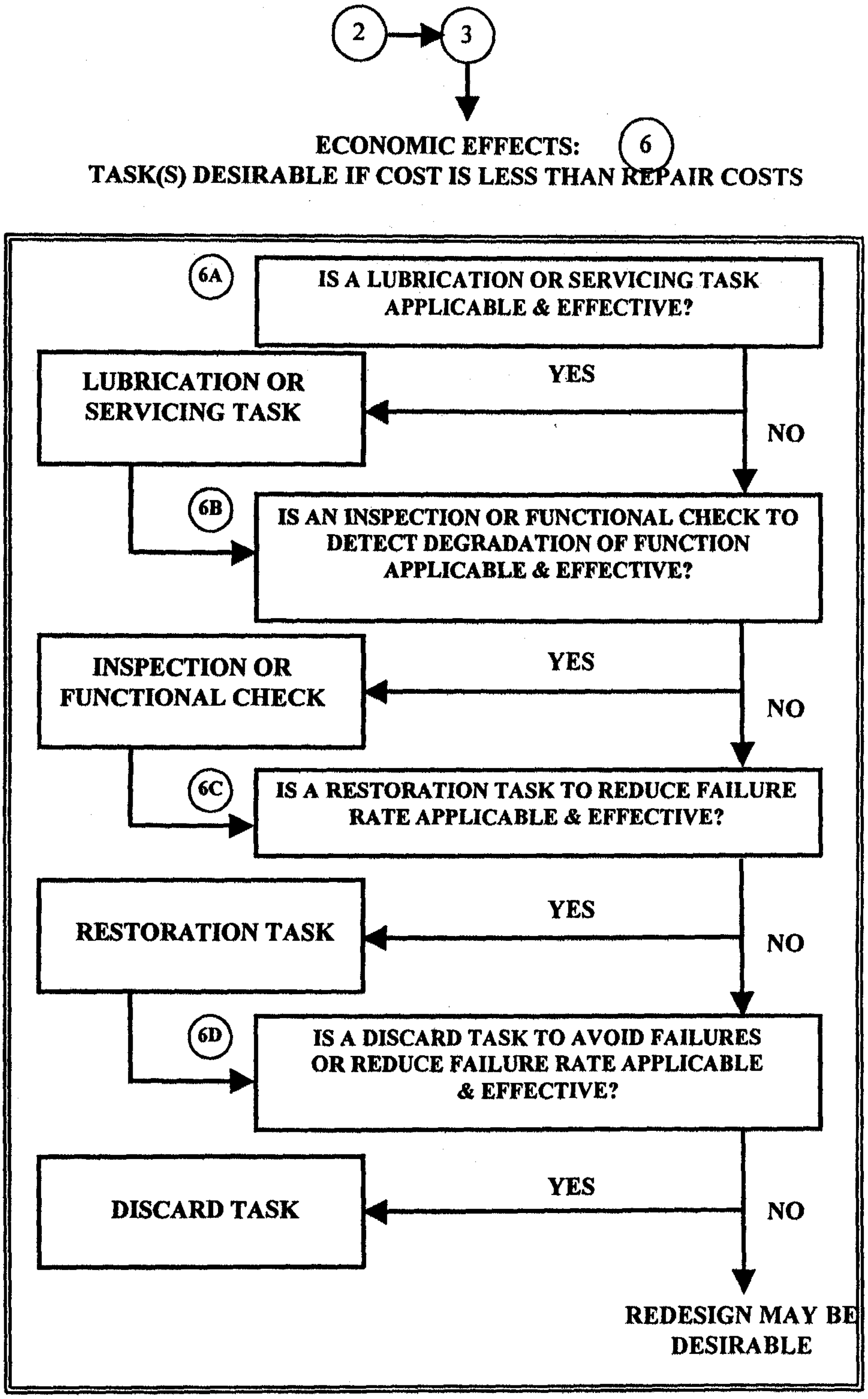


Figure 5-5. Evident failure – economic effects.

h. *Hidden Failure – Hazardous Effects.* The portion of the decision logic tree that deals with situations where a hidden functional failure has a hazardous effect in combination with another failure is shown in figure 5-6. This portion of the tree steps the analyst through a series of questions intended to identify any and all PM tasks that are required to ensure non-hazardous operation. The tasks are effective if they reduce to an acceptable level the probability of occurrence of the functional failure that results in the effects, reduce the effects to purely operational or economic effects, or result in a combination of these.

(1) If none of the PM tasks listed is either applicable or effective, then redesign is mandatory. The reason for making redesign mandatory is obvious. The effects categorized as "hazardous" are unacceptable. Consequently, when PM cannot fulfill any of the objectives listed, we must redesign the product to eliminate the mode of failure that causes the hazardous effects, reduce to an acceptable level the probability of occurrence of the functional failure that results in the effects, or result in a combination of these.

(2) Note that by redesigning to make the failure evident, the effects might be reduced to purely economic or operational.

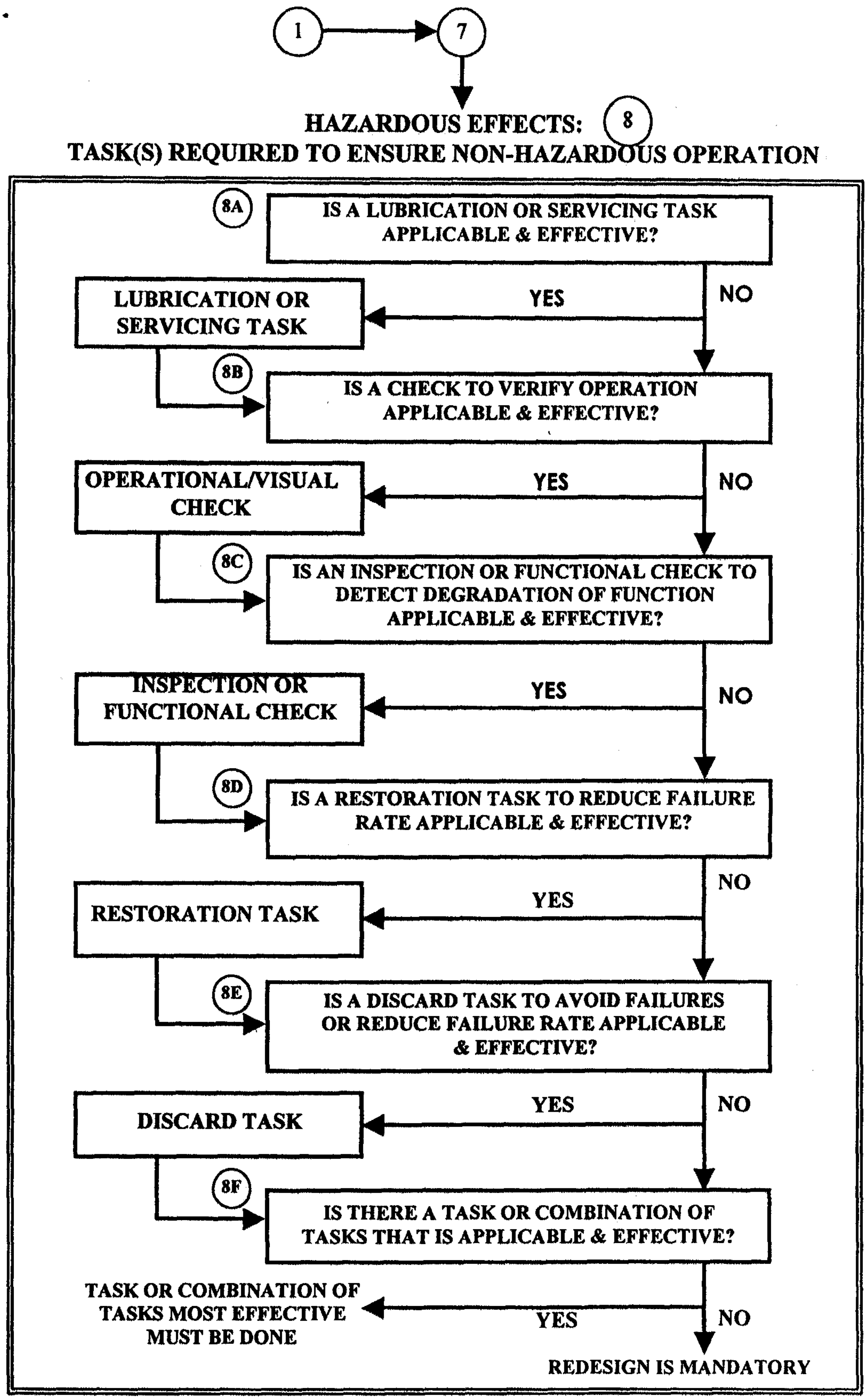


Figure 5-6. Hidden failure – hazardous effects.

i. *Hidden Failure – Non-hazardous Effects.* The portion of the decision logic tree that deals with situations where a hidden functional failure has a non-hazardous effect is shown in figure 5-7. This portion of the tree steps the analyst through a series of questions intended to identify any and all PM tasks that are desirable to ensure availability is sufficiently high to avoid the economic effects of multiple failures. If none of the PM tasks listed is either applicable or effective, then redesign is desirable.

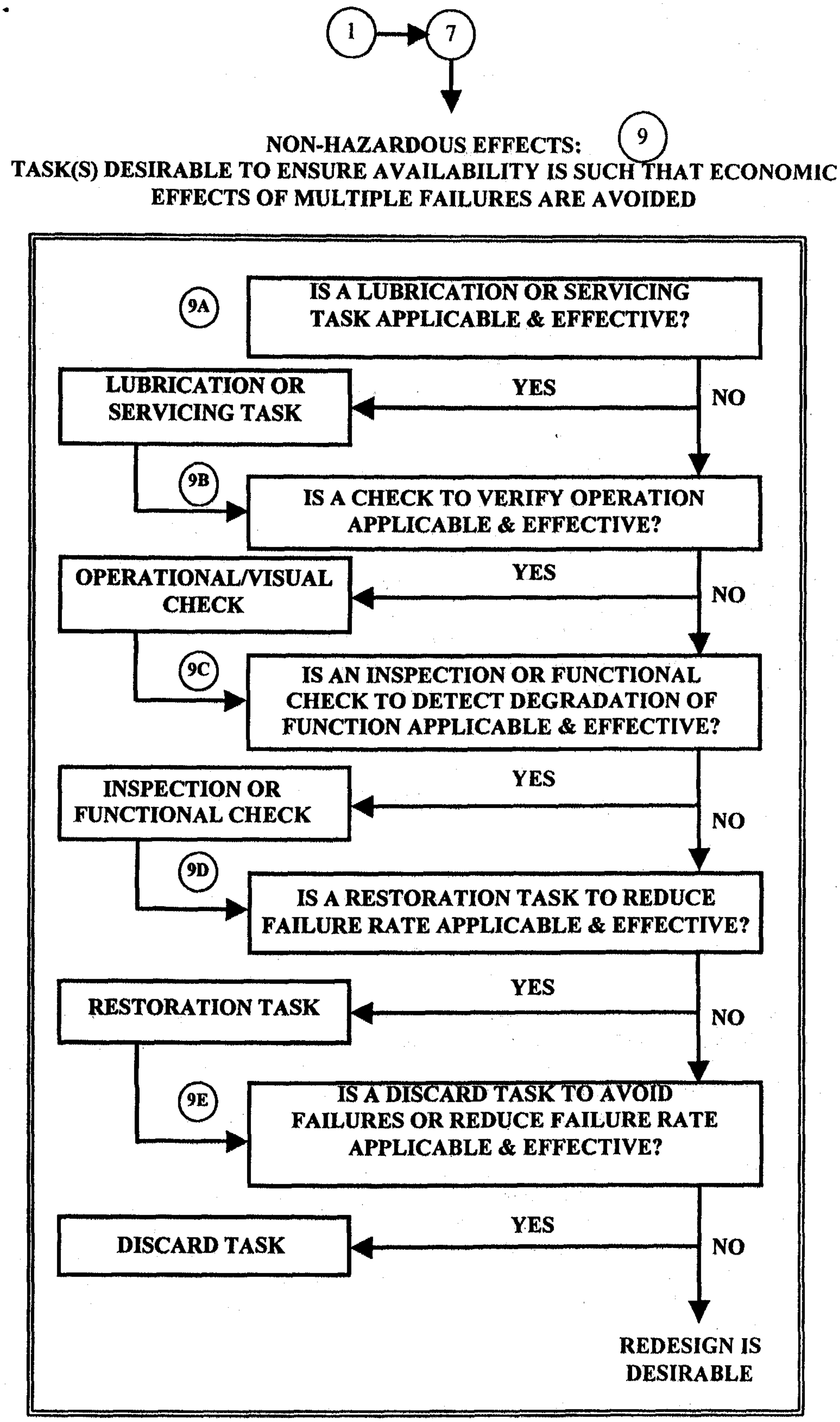


Figure 5-7. Hidden failure – non-hazardous effects.

j. *Package final maintenance program.* As discussed in paragraph 2-4, the result of the RCM analysis will be a set of preventive maintenance (PM) tasks and, by default, a set of corrective maintenance (CM) tasks. PM will consist of on-condition and scheduled maintenance.

(1) *Frequency of tasks.* The frequency with which each of the scheduled PM tasks must be performed will no doubt vary from item to item. It is also probable that many of these tasks may be grouped and performed together at some calendar or operating time interval. The process of grouping the scheduled tasks into sets of tasks to be performed at some prescribed time is called "packaging" the maintenance program.

(2) *Example of packaging.* For example, it may be that for a given product that the scheduled tasks shown in table 5-10 were identified. One way to package these tasks is shown in table 5-11. Note that at the 100, 200, 300, etc. hour points, all of the tasks except the overhaul task are performed. This example is purposely over-simplified and many other factors may (and probably will) have to be considered when packaging the tasks. The point is that by packaging PM tasks, we use our maintenance resources as effectively as possible and minimize the downtime of the product for PM.

Table 5-10. Example of identified tasks

- Three visual inspections: A to be conducted every 45 hours of operation, B to be conducted every 52 hours of operation, and C to be conducted every 105 hours of operation
- A lubrication performed every 55 hours of operation
- A non-destructive inspection every 100 hours of operation
- An overhaul task performed when a stated operating characteristic is out of limits
- A hard-time replacement task every 60 hours of operation

Table 5-11. Packaging the tasks from table 5-4

- Conduct the following PM every 50 operating hours (i.e., at 50, 100, 150, 200, etc.)
  - Visual inspections A and B
  - Lubrication
  - Hard-time replacement
- Conduct the following PM every 100 operating hours (i.e., at 100, 200, 300, etc.)
  - Visual inspection C
- Perform overhaul task whenever the operating characteristic goes out of limits

k. *Continuously improve the maintenance program.* Given the possibility for errors in the initial maintenance program, it is prudent to implement the RCM process as an on-going effort, one requiring perpetual evaluation and adjustment, as depicted in figure 2-1. The process for continuously improving the RCM-based maintenance program consists of Maintenance Audit, Trend Analysis, and Life Exploration. The purpose of this process is to continuously improve the initial maintenance program developed using the RCM concept.

(1) *The initial maintenance program.* The maintenance program that is developed based on the RCM analysis done prior to the first product being delivered to the customer is the ***initial*** maintenance program. This initial program will have been based on the best information that was available at the time the analysis was performed. One of the critical pieces of information is the underlying failure distribution for each item. The information used in the initial RCM analysis was based on a mix of analysis and test results. When "off-the-shelf" items are used in the product, the information can include actual field experience. It must be recognized, however, that some of the information will not be 100% "accurate."

(2) *Maintenance audit.* Auditing the maintenance performed in actual service provides the data needed to refine and improve the maintenance program. In analyzing the data, the maintenance analysts and planners attempt to address the technical content of the program, intervals for performing tasks, packaging of tasks, training, the maintenance concept, and the support infrastructure.

(a) In addressing technical content, analysts and planners must determine if the current maintenance tasks cover all identified failure modes and result in the desired/required level of reliability. Failure modes may have been missed or the current maintenance tasks may not be effectively addressing identified failure modes. The latter may result from incorrectly identifying the underlying failure probability distribution function. Much of this information can be confirmed or updated through a reliability assessment. Table 5-12 lists the type of questions that can be answered by such an assessment.

Table 5-12. Typical questions addressed by a reliability assessment

- Were assessments of useful life too conservative?
- Have replacement intervals been made too short?
- Is wearout occurring later or earlier than anticipated?
- Have the operating conditions or concept changed?
- Has the reliability performance been as expected?
- Have any new failure modes been uncovered?
- Are failure modes identified in development occurring with the expected frequency and pattern (i.e., underlying pdf of failures)?
- Have any modifications to the product been made or are any planned that would add or delete failure modes, change the effects of a given failure mode, or require additional or different PM tasks?
- Were the consequences of failures forecast during development adequately identified?

(b) In addressing performance interval, analysts and planners must determine if the intervals for PM tasks result in decreased resistance to failure. Most often, the objective is to extend the interval as much as possible, without compromising safety, when doing so will reduce costs. Initial intervals are frequently set at conservative levels.

(c) In addressing task packaging, analysts and planners must determine if like tasks with similar periodicity are or can be grouped together to minimize downtime and maximize effectiveness. Lessons learned during actual operation and maintenance may make it necessary to revise the initial packaging.

(d) The analysts and planners should evaluate if available personnel, as currently being trained and using available tools and data, are effectively performing the identified PM tasks. If not, changes to training, procedures, tools, and so forth should be considered.

(e) The analysts and planners should determine if the maintenance concept for the product is effective or should be revised.

(f) The analysts and planners should address the adequacy and responsiveness of the support infrastructure. If the performance of the infrastructure is not as anticipated, recommendations regarding policy, spares levels, and other factors should be considered.

(3) *Trend analysis*. By collecting data on failures, time to failure, effectiveness of maintenance tasks, and costs of maintenance, trends can be identified. The objective of trend analysis is to anticipate problems and adjust the maintenance program to prevent their occurrence. For the RCM effort, two factors typically addressed by trend analysis are the rate of occurrence of failures and maintenance costs.

(a) For trending purposes, at least three data points are needed. The first two establish the trend (positive or negative) and the third serves as confirmation. (In control charting used for quality control, a trend is said to exist when 7 consecutive points continue to rise or fall). However, when measurements are based upon sample surveys over time, data at different points in time may vary because the underlying phenomenon has changed (i.e., a trend exists) or due to sampling error (i.e., the underlying phenomenon has not changed at all). It is not an easy task to sought out the one from the other.

(b) Statistical methods can be used to determine if a trend actually exists. For example, if a system failure rate is actually changing (i.e., it is not constant), the Laplace Statistic will show that a trend exists at a certain level of confidence.

(c) In addition to trend analysis, impending failures can be detected using pattern recognition, data comparison, tests against limits and ranges, correlation, and statistical process analysis.

(4) *Life exploration.* The process of collecting and analyzing in-service or operational reliability data to update the maintenance program is called Life (or Age) Exploration. The data that should be collected during Life Exploration includes historical field service data. Historical field service data typically describes three kinds of maintenance activities: corrective maintenance actions, preventive maintenance action, and service maintenance action.

(a) Historical corrective maintenance data. Corrective maintenance actions occur in response to an operational failure of the system. Corrective maintenance actions are always unscheduled, unwanted, inconvenient, and random.

(b) Historical preventive maintenance data. Preventive maintenance actions occur in accordance with a schedule and are intended to minimize the need for corrective maintenance actions.

(c) Historical service maintenance data. Service maintenance actions are those tasks performed to replenish expended parts and supplies required to operate a system. Many assets require adjustment, replenishment of supplies, lubrication, and cleaning.

5-6. Specific considerations for implementing RCM for C4ISR facilities

a. *Current versus new facilities.* Many C4ISR facilities were built and the mechanical and electrical equipment developed and installed without an RCM analysis having been conducted. Implementing RCM for an existing C4ISR facility, when the current PM program was not based on RCM, is different from implementing it on a facility, new or old, for which the PM program was based on RCM.

(1) *Current PM program in place.* Of course, a program of preventive maintenance will already be in place for an existing facility. Without an RCM analysis, the PM program was probably based on past programs. Indications that the PM program is inefficient or ineffective are an excessive number of corrective maintenance actions (with an associated low facility availability), or an extremely large number of required PM actions that are imposing a very heavy economical penalty. Attempts to change the existing PM program may meet with some resistance (see paragraph 5-6c(3)).

(2) *Need for supporting analyses.* If an RCM analysis was not originally performed for the facility, its systems and equipment, much of the supporting analysis may also have been omitted. If such analyses, such as an FMEA, were not conducted, they must be conducted before an RCM-based PM program can be developed. For many of the installed systems and equipment, performing an FMEA or other analysis may be quite difficult because much of the data may not be available. Either the data was not acquired with the systems and equipment (i.e., data rights were not procured), or the data is missing. In such cases, engineers will have to use engineering judgment and require more time to adequately analyze the systems and equipment.

(3) *Feasibility of redesign.* If following the RCM logic, it is possible that the path may lead to a "Redesign is mandatory" or "redesign may be desirable" outcome. Redesign during initial development is in itself a sometimes-difficult task. Once a system or piece of equipment is in operation, redesign is even more difficult. However, an advantage of a facility is that adding redundancy is less constrained, in terms of space and weight, than for other systems.

b. *Training.* The RCM process is very disciplined and logical. It involves the integration of many different analytical tools, data, experience, and a decision logic tree. Without proper training, those assigned the responsibility of implementing RCM will find it difficult to succeed. Training in the RCM methodology and the related disciplines must be an essential element of an organization's plan for implementing RCM. For C4ISR facilities, especially when maintenance is outsourced (see chapter 6), funding must be provided for training to ensure that an RCM analysis is properly performed. Of course, training to ensure maintenance is properly performed is also essential.

c. *Pitfalls*. In implementing an RCM program in organizations where the concept is new, pitfalls can make implementation ineffective.

(1) *Run to failure shock*. For many maintenance managers and technicians, allowing an item to run to failure runs counter to "conventional wisdom". It is important that they understand the concepts of reliability and turn their focus from preventing failures to preserving function.

(2) *Failure to accept the "Preserve Function" principle*. Most maintenance personnel traditionally have viewed their role as one of preventing failures. To effectively implement an RCM program, it is essential that maintenance personnel focus on preserving the function or functions of an item, not preventing failures.

(3) *Challenging the Past*. Tradition and conventional wisdom remain the principal guidance for many maintenance organizations. Challenging past practices almost always invokes strong resistance, especially if the new practices are not fully understood. Education is the best way to deal with cultural resistance.

(4) *Organization structure*. The RCM process requires close coordination and cooperation among several groups of people, including but not limited to designers, maintainers, and logistic planners. Organizational structures can impede or even prevent the level of cooperation and coordination needed to make RCM a success. The concept of integrated process/product teams (IPPTs) is one that facilitates and encourages cross-discipline cooperation.

(5) *Threat of reduction in staff*. When RCM was first implemented within the airline industry, drastic reductions in scheduled maintenance tasks were made possible. Consequently, the number labor hours and people required to, for example, conduct structural inspections of an aircraft were significantly reduced. When a segment of an organization perceives that a new policy or procedure will eliminate their jobs, the natural reaction is to fight against the new policy or procedure. However, with vision and planning, management can find ways to effectively use the resources freed up by implementing RCM and minimize the impact on jobs by using normal attrition, cross training, etc.

(6) *Inadequate buy-in*. All too often, management implements a new policy or procedure without fully supporting that policy or procedure. If either resources or management interest is insufficient, the new policy or procedure will probably fall short of expectations. This is especially true for RCM, an approach that is often met with skepticism and resistance by the very same people who must help implement it.

(7) *Informal procedures*. RCM is a very structured, disciplined method of developing a comprehensive and effective maintenance program. It cannot be effectively implemented on an informal or ad hoc basis. The procedures for implementing an RCM approach within an organization must be formal, documented, and managed.

(8) *Inadequate data collection*. If the underlying pattern of failures for a given item is unknown, one cannot objectively determine if PM should be considered. Without adequate information regarding the frequency of failure or the parameters of the failure probability density function, one cannot objectively determine when a PM task should be performed. Data that is adequate in both quantity and type (e.g., time to failure) is essential to the RCM process.

5-7. Evaluation of alternatives

As a result of performing an RCM analysis, alternatives will present themselves. These alternatives fall into two categories: Maintenance Tasks and Designs. Both categories are a natural result of the RCM analysis. In examining the logic trees in paragraph 5-5, it is obvious that more than one type of maintenance task may be applicable and effective for a given failure. Also, in some cases, for example where the effects of a failure are hazardous or a hidden failure can occur, redesign is mandatory or desirable. How do we determine which tasks to perform? How do we select the "best" design change (e.g., in the case of failures with hazardous effects) or determine if a design change is cost-effective (e.g., in the case of a hidden failure). We can address these questions using Trade-off Studies, Operational Analysis, and Cost-Benefit Analysis.

a. *Trade-off studies*. Designing a new system or a change to an exiting one, even a moderately complex one, requires a series of compromises. These compromises are inevitable, given the fact that requirements often conflict. Design decisions necessary to meet one requirement may result in another requirement not being met. For example, strength and fatigue life requirements drive the selection of materials and the size (bulk) of structures in one direction. The maximum weight requirement drives these same factors in the opposite direction. Systems engineering is the process of selecting design solutions that balance the requirements and provide an optimized system. Usually, this balance means that some requirements may not be fully met. The process of selecting one design solution over another is often referred to as design trade-offs. Trade-off studies consist of the steps shown in table 5-13.

Table 5-13. Steps in design trades

• Compare two or more design solutions
• Determine which provides the best results given cost and schedule constraints
• Determine if the system requirements can be met with the selected design solution
• If the system requirements cannot be met, determine the budget and schedule required to support a design solution that does allow the system requirements to be met, or re-evaluate the requirements

(1) *RCM and desired design changes*. An RCM analysis may indicate that a change to the design is required or desirable. In such cases, trade-off studies will probably be needed to determine if a solution can be found that is effective (affordability is addressed in a cost-benefit analysis – see paragraph 5-8c).

(2) *RCM and mandatory design changes*. When the RCM analysis shows that two or more PM tasks are applicable, trade-off studies will be needed to determine which task(s) is (are) most effective. Of course, when a specific failure has hazardous effects, <u>redesign is mandatory</u> if no PM tasks are effective and applicable.

b. *Operational analysis*. To determine if a specific failure has operational effects (but no hazardous effects), an analysis of the operational concept is necessary. This analysis addresses the impact of a given failure on measures of operational performance. The measures are a function of the type of product and how that product is used. For the airline industry, for example, the cost of an operational failure includes lost revenue, potential penalties (in the form of compensation to passengers), loss of customer confidence and loyalty, and the cost of fixing the failure. For a military organization that operates aircraft, the costs might include a decrease in readiness, the inability to fulfill a mission, the cost of reassigning another aircraft to replace the original aircraft, and the cost to fix the failure. For a commercial company, the cost of an operational failure of a product could include the loss of customer confidence and loyalty, the cost of repair under warranty, and possible claims by the customer for lost revenue or other non-hazardous effects of the failure.

c. *Cost-benefit analysis*. Another type of analysis frequently used whenever one of two or more alternatives (design A vs. design B, task 1 vs. task 2, process I vs. process II, etc.) must be selected is a cost-benefit analysis (CBA).

(1) *Potential benefits*. In a CBA, the potential life-cycle benefits of and life-cycle costs to implement a given alternative are compared with those of the other alternatives. One of the most difficult steps in a CBA is finding a common basis for comparison. That basis is almost always dollars, since the costs of implementing a choice can almost always be directly measured in terms of dollars. Some of the benefits of an alternative may be intangible. However, it may be possible to attach a dollar value to even these benefits. Benefits to which a dollar value cannot be assigned should be evaluated and assigned relative numeric values for comparison purposes. For example, a maximum benefit could be assigned a value of 5, an average benefit a value of 3, and a minimum benefit a value of 1. Evaluating and comparing benefits that have both dollar values and relative numeric values requires extra effort, but it allows all benefits to be considered in the analysis.

(2) *Costs*. In a simple CBA, the annual costs of implementing each alternative design change, for example, are estimated. For this purpose, the analyst would sum up the estimates of the costs shown in table 5-14. The analyst

would estimate the annual benefits of the first alternative and then repeat this process for each of the other alternative design.

Table 5-14. Typical costs considered in cost-benefit analysis

- The cost of the labor hours needed to develop the design
- The cost of any additional testing required
- Any differences in materials costs
- Changes in manufacturing costs
- Additional costs due to changes in schedule
- Other costs

(3) *Conversion.* The analyst must convert the annual estimates to a common unit of measurement to properly compare competing alternatives. This conversion is done by discounting future dollar values, which transforms future benefits and costs to their "present value." The present value (also referred to as the discounted value) of a future amount is calculated using equation 4.

$$PV = FV/(1 + i)^n \qquad \text{Equation 4}$$

where:

PV = Present Value
FV = Future Value
i = Interest rate per period
n = Number of compounding periods

(4) *Comparison.* When the costs and benefits for each competing alternative have been discounted, the analyst compares and ranks the discounted net value (discounted benefit minus discounted cost) of the competing alternatives. In the ideal case one alternative will have the lowest discounted cost and provide the highest discounted benefits – it clearly would be the best alternative. More often, however, the choice is not so clear-cut, and other techniques must be used to determine which alternative is best.

(5) *Dollar values.* Earlier, it was mentioned that some benefits may not quantifiable in terms of dollars and may have relative numeric values assigned for comparison purposes. In those cases, these numeric values can be used as tie breakers if the cost figures do not show a clear winner among the competing alternatives, and if the non-quantifiable benefits are not key factors. If they are key factors, the quantified benefits can be converted to scaled numeric values consistent with the non-quantifiable benefits. The evaluation then consists of comparing the discounted costs and the relative values of the benefits for each alternative. When the alternative with the lowest discounted cost provides the highest relative benefits, it is clearly the best alternative (the same basic rule used when you have discounted benefits). If that is not the case, the evaluation is more complex.

(6) *Numerical values.* Finally, if no benefits have dollar values, numerical values can be assigned (using some relative scale) to each benefit for each competing alternative. The evaluation and ranking are then completed in the manner described in the previous paragraph.

(7) *Sensitivity analysis.* Sensitivity analysis can be used to test the sensitivity and reliability of the results obtained from a CBA. For more information on conducting a CBA and related analysis, see the references in appendix A.